TECHNICAL REPORT ARLCB-TR-82018

THE SLIDING BEHAVIORS OF COPPER ALLOYS

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June 1982

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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AMCMS No. 611102H600011

DA Project No. 1L161102AH60

PRON No. 1A2250041A1A

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1. REPORT NUMBER: ARLCB-TR-82018	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): THE SLIDING BEHAVIORS OF COPPER ALLOYS	5. TYPE OF REPORT & PERIOD COVERED: Final
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): R. S. Montgomery	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: US Army Armament Research & Development Command, Benet Weapons Laboratory, DRDAR-LCB-TL, Watervliet, NY 12189	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: AMCMS No. 611102H600011, DA Project No. 1L161102AH60, PRON No. 1A2250041A1A
11. CONTROLLING OFFICE NAME AND ADDRESS: US Army Armament Research & Development Command, Large Caliber Weapon Systems Laboratory, Dover, NJ 07801	12. REPORT DATE: June 1982
	13. NUMBER OF PAGES: 41
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Presented at Gordon Conference, New London, NH, 14-18 June 1982.
To be presented at International Conference on Wear of Materials, Reston, VA, 11-14 April 1983.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Friction	Sliding	M650 Projectiles
Wear	Chromium Electroplate	M549 Projectiles
Scuffing	Tantalum	Microstructure
Metal Transfer	Rotating Bands	Hardness
Copper Alloys	M483 Projectiles	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The unlubricated behaviors of a number of copper alloys and especially their metal transfers and scuffing tendencies were investigated on steel, chromium electroplate, and tantalum using a specially designed pin-on-disk friction and wear machine. This machine limited the sliding time to about 100 msec. It was not possible to correlate metal transfer, scuffing (rough deposits), or friction with the properties of the alloys. There was a correlation of wear with

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20. ABSTRACT (Cont'd)

hardness for similar alloys with higher hardness alloys having lower wear. The effect of hardness was different for different mating surfaces. The data from aluminum bronze and the welded overlay rotating band materials investigated did not fall into this correlation. This could not be attributed to a special microstructure or to crystalline orientation in the case of the welded overlay band materials. Mutual solubility of the pin and disk metals and relative position in the periodic table also did not control metal transfer and scuffing with the copper alloys investigated. While position in the periodic table is identical and mutual solubilities are certainly very similar for most of the copper alloys, there were great differences in metal transfer and scuffing. While there was a tendency for more transfer to occur at higher wear rates, heavy and very heavy transfer do occur even at very low rates. Heavy and very heavy transfer were not usually associated with high wear and rough deposits were not usually associated with high wear and heavy transfer. The first step in wear was not transfer to the mating surfaces. In addition, small amounts of iron in the copper alloys did not result in scuffing and high metal transfer even when sliding on steel.

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ACKNOWLEDGEMENTS

Most of the experimental work was done by L. J. Szymanski and some of the initial work was done by K. J. Lansing. The metallography was done by Theresa Brassard and C. Rickard. The x-ray study was done by G. Capsimalis.

INTRODUCTION

Metal surfaces sometimes scuff and adhere to each other during sliding. It is believed that much of the severe wear sometimes shown by projectile rotating bands is caused by scuffing of their surfaces during engraving and initial travel before a lubricating molten film has been formed. Previous investigations of the scuffing of sliding metals have been chiefly empirical. Some metal pairs scuff and some do not. The purpose of this research is to develop a basis for prediction of scuffing of copper alloys and hopefully of other metals. While scuffing is the primary focus of this research, metal transfer, wear, and coefficients of friction were also measured to obtain an insight into the phenomenon.

Metal transfer or pickup is clearly related to wear because there can be no metal transfer without some wear. Kerridge,[1] studying the wear of a radioactive, annealed steel pin sliding on a hardened steel ring, found that metal transfer was equal to the initial wear of the annealed steel and concluded that the first step in the production of loose wear particles was transfer to the counterface. The particles of metal worn from one surface can either be retained on the other surface and/or they can come off in the form of loose wear particles. In addition, transferred metal can be rough (precursor to scuffing) or smooth. If it is rough, it can have a great effect on wear during subsequent passes and can result in seizure and catastrophic failure. Erickson[2] reported that metal transfer consistently correlated with wear for all the metals in his study. However, in the case of two metals out of the total of eight the wear was very low, and, since he used multiple

References are listed at the end of this report.

passes, wear would be greatly influenced by the topography of the mating surface. Indeed, the pair which produced severe scratches also produced the highest wear. Therefore, the reported correlation of metal transfer with wear is not convincing.

There is no correlation between metal transfer and coefficient of friction,[3] although since it is known that increased temperature causes increased adhesion,[4,5,6] it might be expected that increased heat generation because of higher friction would result in greater metal transfer. The extreme of adhesion is seizure where all sliding of the surfaces stops. Mutual solubility has been considered the most important factor in the metal transfer or seizure of metals. Goodzeit[7] stated that scuffing of two metals was principally determined by their alloying characteristics (mutual solubility). He pointed out that surprisingly, some miscible pairs have fair resistance to seizure and some immiscible pairs have poor resistance to seizure. Ernst and Merchant[8] suggested that mutual solubility should be a factor in friction and wear - the best metal pairs being those that are immiscible. Roach et al[9] stated that while mutual solubility of pin and disk metals is necessary to avoid seizure, another factor measured by the metal's position in the periodic table is also required. Oberle[10] pointed out the importance of elasticity and suggested the ratio of hardness to the coefficient of elasticity as a guide to sliding behavior. His reasoning was that greater elasticity of the surface would better distribute the load and lower the contact stress. He further stated that modulus tends to decrease as the melting point increases. Soft, low-melting point alloys are most susceptible to surface welding but suffer little damage because of the ease with which they break a welded bond by localized

softening. High-melting point metals, on the other hand, seize and weld with resultant destruction of the surface area or the entire part. Therefore, the melting points of metals in contact influence tendencies toward seizure both because of the melting points themselves and also because of their effect on elasticity. Oberle also states that there is tendency for elastic modulus to decrease as atomic volume increases. Drozdov and Archegov[11] used the same ratio of hardness to coefficient of elasticity as did Oberle but since they took the modulus of elasticity as constant, they concluded that the tendency to scuff decreased with increasing hardness. They did not give the extent of their investigations or specify the metals studied.

Wear often correlates with hardness although Oberle is certainly correct that hardness has been overemphasized as a wear preventive property. Montgomery,[12] in a lubricated wear study on a number of lead-containing bearing bronzes, found that hardness is not a completely reliable guide to wear resistance. With a hard slider on a bronze ring, there was a general trend toward lower wear rates with increasing hardness of the bronze; but there was no effect of hardness with the opposite sliding geometry. (This is probably in agreement with the results of the friction study of Moore and Tegart.[13]) Erickson[2] in a similar study of bearing materials, found no consistent influence of hardness or indeed of any bulk property on wear behavior. However, Archard[14] devised an expression for wear which is widely accepted as a good estimate where wear is inversely proportional to hardness. Lancaster[15] also found that the wear rate of 60/40 leaded brass varies inversely with the hardness of the brass when the latter is changed by external heating. As stated above, Oberle pointed out the importance of elasticity to wear. He stated

that wear sometimes increases as hardness increases so that the ratio of hardness to the coefficient of elasticity would be a better guide than hardness alone. While the effect of elasticity seems reasonable, he did not consider such important factors as mechanism, important impurities, and surface structure. These factors strongly affect his particular examples. Peterson et al, in their review of wear,[16] state that adhesive wear rates are proportional to adhesive bond strength and ductility, and Keller[6] states that the adhesion coefficient increases with increasing ductility and decreases with melting point.

It has often been suggested that a high coefficient of friction is caused by a high adhesion between the surfaces.[4,17-21] Sikorski[20] reported that there is a good correlation between the coefficient of friction and the median coefficient of adhesion. Since friction and adhesion were determined in the same experiment, it is not surprising that they are related. Furthermore, his results are only convincing for FCC metals. Oberle[10] refers to work reported by Kontorovich and Arkherov[22] where friction of metals in sliding contact is lowest for metals of high modell (i.e., the ratio of hardness to coefficient of elasticity). It has also been stated that friction is inversely proportional to hardness.[11,19,20,23,24] However, Moore and Tegart[13] found that while the coefficient of friction of a hard material sliding on the softer beryllium copper was markedly dependent on the hardness of the beryllium copper, it was very erratic and there was no such relationship when the slider was softer than the plate. This was also confirmed in experiments with beryllium copper sliders on beryllium copper. Friction decreased linearly with hardness in the regions where the slider was harder than the

plate but remained constant in the regions where the slider was softer.

The behaviors of copper alloys in dry sliding on steel, while pertinent to the study of the sliding of projectile rotating bands on cannon bores, were expected to be irregular. Rabinowicz and Tabor[3] reported that copper sliding on mild steel resulted in over three times the metal transfer as did steel sliding on copper. On the other hand, Goodzeit[7] reported that copper on steel usually runs fair (i.e. the pair fails at high load in the test machine) but when the geometry was reversed and the hard metal slid on the softer one, the pair performed poorly. In addition, Roach et al[9] reported that copper sliding on a steel disk marginally lubricated with kerosene exhibited erratic behavior. It rated high in the "fair" class in some tests and low in the "poor" class in others. Anderson[19] reported that there was no correlation between the median coefficient of adhesion and hardness for copper and attributed this to work hardening. Semenov[5] states that the influence of chemical composition on seizure is shown to be considerable in the case of copper alloys. Merchant[25] reported that there was no scoring between the copper-iron pair in his tests. He also pointed out that copper and iron are quite mutually insoluable at room temperature, but that their solubility becomes very considerable at temperatures such as those occurring at contact points of sliding surfaces. However, molten copper has been reported not to wet iron.[26,27]

There is not much information about copper sliding on either chromium or tantalum; but Goodzeit[7] reported that a chromium slider performed fairly well when run against a copper disk, but a tantalum slider had poor resistance to seizure. Copper is immiscible with chromium and with tantalum.

EXPERIMENTAL METHOD

The present study was carried out using a "pin-on-disk" friction and wear machine. With this machine a pin is pressed against the surface of a rotating disk. The coefficient of friction was determined from instantaneous measurements of load and friction forces; wear was determined by measurements of changes in length of the test pin and reported as 0.025 mm (0.001 inch) of wear; and amount and character of metal transferred from the pin to the rotating disk were estimated by visual observation.

The design of the test machine was fairly typical. Differences between it and usual pin-on-disk machines are related to the extremely soft and rapid-wearing pin materials. The method used for bringing the pin into contact with the disk for an extremely short time is novel. The pin is loaded with a "nutcracker" arrangement by means of a pneumatic cylinder fastened to the end of the loading arm. The arm which is continually loaded is held out of contact with the disk supported by means of a rotating cam and sear arrangement. When the sear is triggered, the pin is let down a very short distance into contact with the rotating disk and then quickly picked up again by the rotating cam. The sear then reengages thereby preventing the pin from again contacting the disk.

The disk was 305 mm (12 inches) in diameter and 32 mm (1-1/4 inches) thick. It was made from AISI 4340 steel and was not heat treated. This steel approximates the composition of conventional gun steel. The surface of the disk was used to obtain data for the pins sliding on steel. Plates of tantalum and chromium electroplated steel fixed to the rotating steel disk were used to obtain data for pins sliding on these materials. The disk was

designed to be of relatively large mass so that its rotational speed would not change during an experiment. The properties of the disk surface materials are given in Table I.

TABLE I. PROPERTIES OF THE DISK METALS

	4340 Steel	Chromium Electroplate	Tantalum
m.p. (°C)	1530°	1890°	3000°
Conductivity ($cal/cm^2/cm/sec/°C$)	0.108	0.16*	0.130
Elast. Mod. (kN/m^2)	200×10^6	110×10^6	186×10^6
Hardness (KHN)	235	1000	140
$\sigma_u (kN/m^2)$	744,000	103,000	758,000
$\sigma_y (kN/m^2)$	472,000	103,000	690,000
Elongation (%)	22	0	3

*From fused salt deposition.

The pin was plane-ended and 4.75 mm (0.187 inch) in diameter. One pin was used for a number of experiments; the exact number depended on its wear rate. In the work reported at this time, pins were made of OFHC copper; sintered copper; two copper alloys containing iron (0.31 and 1.20 wt. %); two dispersion hardened coppers (Glidcop AL-20 and AL-60 with 0.4 and 1.1 wt. % aluminum oxide respectively); gilding metal (90-10 copper zinc alloy); an aluminum bronze; and welded overlay band materials from recovered M483 (gilding metal), M549 (copper), and M650 (copper) projectiles. Unfortunately, the material from the band of the recovered M483 projectile was not actually gilding metal and was not within specifications. It contained a large amount of

aluminum. In the case of the welded overlay band materials, directionality is doubtlessly important and pins were machined from the bands with their axes perpendicular to those of the projectiles. In this way sliding of the pins was the same as for actual bands sliding on a cannon bore. The copper alloys containing iron were made from powders of the individual metals and were heat treated to eliminate the sintered microstructure. The compositions and properties of all the pin metals are given in Tables II and III.

The rotational speed of the disk was obtained by measuring the pulse rate produced by a light beam passing through eight equally spaced holes around the periphery of the disk. The experiments described in this report were made at a sliding speed of 1.7 m/s (67 inches/sec). This corresponds to projectile velocities close to the origin-of-rifling in a cannon where sliding is unlubricated metal-on-metal and compatability is important.

The values of both instantaneous load and friction force were obtained from outputs of strain gages. The bearing load was obtained from a commercial strain-gaged stud located between the pin-holder and the load arm. The friction force was obtained from strain gages mounted on the leading and trailing surfaces of the pin-holder which measured its very slight bending. Unfortunately, there was some interaction so that the coefficient of friction was not the simple ratio of outputs. The length of the pin projecting from the pin-holder before the experiment was measured for the wear determination and was also taken into account in the computation of the friction force. This length affected the calibration of the friction force strain gages. Bearing pressures ranged between 55,000 kN/m^2 (8,000 psi) and 83,000 kN/m^2 (12,000 psi). The lower limit was high enough so that there was usually little change in coefficients of friction with bearing pressure.

TABLE II. COMPOSITIONS AND PROPERTIES OF THE COPPER ALLOYS

	OFHC Cu	Sintered Cu	0.31% Fe Cu	1.20% Fe Cu	AL-20 Cu	AL-60 Cu	Gilding Metal
Cu (wt. %)	100.	99.82	99.44	97.92	99.6	98.9	90.0
Fe (wt. %)	0	0.012	0.313	1.197	-	-	0
Zn (wt. %)	0	0	0	0	-	-	10.0
Al_2O_3 (wt. %)	0	0	0	0	0.4	1.1	0
O_2 (wt. %)	0	0.09	-	-	-	-	-
Hardness (KHN)	88	73	70	77	174	175	85
m.p. (°C)	1083°				1082°	1082°	1021-1043°
Conductivity (cal/cm^2/cm/sec/°C	0.958				0.843	0.768	0.450
Mod. of Elast. (kN/m^2)	110×10^6	110×10^6	110×10^6		113×10^6	137×10^6	137×10^6
σ_u* (kN/m^2)	220-240,000				470,000	520,000	258,000
σ_y* (kN/m^2)	69-76,000				370,000	450,000	69,000
Elongation (%)*	45-55				19	10	45

*With no cold work.

TABLE III. COMPOSITIONS OF ROTATING BAND AND ALUMINUM BRONZE ALLOYS

	Band Mat'l from M483	Band Mat'l from M549	Band Mat'l from M650	Aluminum Bronze
Cu (wt. %)	85.25	96.74	96.77	87.22
Fe (wt. %)	1.58	1.25	2.07	2.31
Zn (wt. %)	7.46	0	0.02	0
Al (wt. %)	5.21	0	0	9.72
Sn (wt. %)	0.34	0.99	0.68	0
Hardness (KHN)	132	144	137	146

The data reported at this time are for pins sliding on smooth, fresh surfaces. They were produced by removing all traces of transferred metal by abrading with 100 grit emery cloth at speed, then polishing with 400 grit emery at speed, and wiping with soft paper to remove any traces of grit, etc. also at speed. In later experiments, the disk was then wiped with soft paper wetted with methyl ethyl ketone and dryed with soft paper in order to remove any possible traces of contamination from the surface. In some preliminary experiments petroleum ether was used. In neither case did this final cleaning with either solvent make any apparent difference.

The pin was matched to the disk before the first sliding experiment (i.e. there was complete contact on the bottom surface of the pin). In spite of this, the friction results from the first experiment with a fresh pin were sometimes different from the results of succeeding experiments. If this was the case, all the friction measurements from that experiment were discarded.

Measurement of wear by pin length changes was neither extremely sensitive nor precise. Sometimes there was metal transfer but the measured wear was zero (i.e. the pin length appeared unchanged). Changes in pin length, because of distortion were rare, but when there was some doubt, wear values were discarded. Four experiments were routinely conducted with each metal pair. Each yielded 33 pieces of friction data and one wear determination. Often two and sometimes more series were made with a particular pair. On the other hand, in the first few experiments, only three determinations were made with each metal pair and if there was little scatter in this data, another series was not made. Instantaneous values of the coefficient of friction were obtained from the instantaneous friction force and load measurements. The outputs of the strain gages were recorded using a digital oscilloscope because of the short duration of that portion of the experiment producing friction data. Friction data were taken from the first portion of the experiment after almost full load was reached. Typical contact times were about 100 msec. Friction data were never taken during the very short time of sliding at the end of an experiment when the pin was sliding on a previously contacted part of the disk. Friction data were also not taken at loads below 890 N (200 lbf). Wear was taken as the length of pin lost during an experiment and measured to the nearest 0.025 mm (0.001 inch). Metal transfer was estimated visually as none, very slight, light, moderate, heavy, or very heavy. The transferred metal was rough only occasionally except for M650 projectile band material sliding on both steel and tantalum where the deposit was always rough.

DISCUSSION

The eleven copper alloys used as pin materials in this research are of interest in explaining the sliding behavior of projectile rotating bands. They also are a group of metals with very similar melting points, chemical properties, and modulus of elasticity. On the other hand, their hardnesses and microstructures are very different and their ductilities quite different. Unfortunately, the propensity of copper alloys to work harden introduced some difficulty into efforts to find correlations with mechanical properties.

The three disk materials investigated, tantalum, AISI 4340 steel, and chromium electroplate, are of interest or potential interest as bore surfaces in cannons. Most cannon bores are of gun steel which is closely approximated by AISI 4340; in some cannons the steel bore is protected by a coating of chromium electroplate; and liners of tantalum or of tantalum alloys are being considered because of their resistance to "erosion". In addition, these three metals are very different in their chemical, physical, and mechanical properties. Although they are all more or less immiscible with copper, probably steel (or iron) has the highest solubility.

The pin-and-disk apparatus used in this study provides a guide to the sliding behavior of a metal pair but does not simulate the sliding of a projectile on the bore of a cannon. Therefore, the results of the experiments must be modified somewhat for this application. It is not possible to reach the very high bearing pressures with this apparatus because of distortion of the relatively soft pin metals. In an actual cannon, the band material is confined and the bearing pressures during engraving usually are three or more times the values used in this study. In addition, the data are for copper

alloys sliding on clean, smooth surfaces. The situation in an actual cannon is more complex. The bore is often not smooth at the origin-of-rifling and it is generally contaminated with powder residue and band material from previous rounds. However, the clean, smooth surface is reproducible and it gives a good indication of the actual sliding behavior. In general, roughness increases the coefficient of friction and the wear rate, while surface contamination decreases both of them. Contamination also decreases metal transfer to the counterface.

Metal Transfer

Data from the sliding experiments are given in Tables IV and V and wear as a function of metal transfer is shown in Figure 1. There was extreme variation in the wear and transfer data for those pairs where either could be high. This extreme variation doubtlessly resulted from the very small sliding area and very short time of sliding. This result raises the possibility that heavy transfer and/or high wear would have been obtained with more of the copper alloys if more experiments had been performed. In any case, heavy or very heavy transfer occurs with AL-60 copper and sintered copper sliding on 4340 steel and also with 0.31 percent Fe containing copper, band materials from M483, M549, and M650 projectiles, and with aluminum bronze sliding on tantalum. Heavy or very heavy transfer did not occur with any of the copper alloys studied sliding on chromium.

While there was a tendency for more transfer to occur at higher wear rates, heavy and very heavy transfer occurred even at zero wear* (measured to the precision of the experiment). The least squares intercept (i.e. wear at no

*Zero wear in this report implies wear less than 0.025 mm, the limit of the experimental measurement.

TABLE IV. AVERAGE RESULTS FROM SLIDING EXPERIMENTS

	Cu OFHC	Cu Sintered	Cu 0.31% Fe	Cu 1.20% Fe	Cu AL-20	Cu AL-60	Gilding Metal	
$\bar{f}$	0.30 ± .03	0.39 ± .01	0.30 ± .02	0.40 ± .01	0.33 ± .01	0.33 ± .01	0.45 ± .02	Steel
wear (mm)	0	0.02	0.06	0.04	0	0	0.01	
transfer	none to light	very slight to heavy	none to light	very slight to light	none to light	moderate to very heavy	light	
rough	no	occasionally	no	no	no	occasionally	no	
$\bar{f}$	0.52 ± .05	0.36 ± .03	0.38 ± .03	0.35 ± .02	0.38 ± .02	0.39 ± .02	0.27 ± .02	Cr Plate
wear (mm)	0.005	0	0.03	0.005	0	0	0	
transfer	none	none	very slight to moderate	none	none to very slight	none	none	
rough	no	no	occasionally	no	no	no	no	
$\bar{f}$	0.33 ± .02	0.35 ± .03	0.33 ± .01	0.38 ± .03	0.31 ± .02	0.37 ± .01	0.37 ± .01	Ta
wear (mm)	0.01	0.008	0.025	0.025	0.008	0.005	0.02	
transfer	very slight to light	none to very slight	very slight to heavy	none to very slight	very slight	very slight	light to moderate	
rough	no	no	no	no	no	no	occasionally	

$\bar{f}$ = average coefficient of friction.

TABLE V. AVERAGE RESULTS FROM SLIDING EXPERIMENTS

	M483 Projectile Band Mat'l	M549 Projectile Band Mat'l	M650 Projectile Band Mat'l	Aluminum Bronze	
$\bar{f}$	0.35 ± 0.01	0.29 ± 0.03	0.40 ± 0.02	0.38 ± 0.02	Steel
wear (mm)	0.02	0.25	0.02	0.01	
transfer	v. slight to light	v. slight to moderate	moderate	v. slight to light	
rough	no	occasionally	yes	no	
$\bar{f}$	0.25 ± 0.04	0.32 ± 0.02	0.38 ± 0.03	0.32 ± 0.02	Cr Plate
wear (mm)	0.0025	0	0.0025	0.005	
transfer	none to light	none	none to light	none	
rough	no	no	no	no	
$\bar{f}$	0.40 ± 0.02	0.29 ± 0.02	0.28 ± 0.02	0.29 ± 0.03	Ta
wear (mm)	0.085	0.15	0.02	0.045	
transfer	v. slight to v. heavy	light to heavy	light to v. heavy	moderate to v. heavy	
rough	occasionally	occasionally	yes	occasionally	

$\bar{f}$ = average coefficient of friction.

metal transfer) was 0.0066 mm wear which is consistent with wear measured to the nearest 0.025 mm in the experiment. The transferred metal was rough in a minority of the cases. If experiments with none, very slight, and light transfer were not considered, there would be no correlation between wear and metal transfer. Even rough transferred metal was not usually associated with high wear or heavy transfer. In about 30 percent of the cases of a rough deposit, wear was measured as zero (>0.025 mm) and metal transfer in the majority of cases where a rough deposit was obtained was only moderate.

Mutual solubility with a particular disk metal, melting point, elasticity, and chemical properties of all the copper alloys are about the same, but metal transfer was sometimes very different. Therefore, these properties could not be the controlling factor. Also there was no correlation with either hardness or ductility of the pin materials. In addition, small amounts of iron in the copper did not lead to transfer or scuffing even in sliding on steel. Even microstructure is not the important factor controlling metal transfer. The microstructures of AL-60 and AL-20 coppers are identical as are those of copper containing 0.31 percent Fe and copper containing 1.20 percent Fe, while the sliding behaviors of the former on steel and the latter on chromium electroplate were very different. High transfer was encountered in more cases of the copper alloys sliding on tantalum than in cases of the copper alloys sliding on steel although in many cases only light or very slight transfer was obtained.

Wear

An important observation from this study is that both metal transfer and wear of aluminum bronze and the welded overlay band materials (from the M483, M549, and M650 projectiles) were essentially different from the other copper

alloys investigated. These alloys often scuff and sometimes transfer to the mating surfaces more and show unexpectedly high wear. (However, this is not true for the alloys sliding on chromium electroplate.) Aluminum bronze transfer and wear behavior seems easy to understand. The copper content of the alloy is only 88 wt.% and the microstructure shows a large proportion of needles of different composition in the matrix (see Figure 2). However, the transfer and wear behavior of the welded overlays seem more difficult to explain. Although the difference in the case of material from the band of the M483 projectile could be attributed to chemical composition, it certainly can not in the cases of the alloys from the bands of M549 and M650 projectiles. These alloys are 96.74 percent and 96.77 percent copper, respectively. It also apparently cannot be attributed to microstructure. The microstructures of the alloys behaving differently show a wide variation. Gilding metal (Figure 3) and OFHC copper (Figure 4) both have annealed structures of relatively small grains; copper containing 0.31 and 1.20 percent Fe have heat treated structures of large grains (Figure 5); AL-20 and AL-60 coppers are dispersion hardened alloys with grains so small that they cannot be resolved even at 1000X (Figure 6); and sintered copper has a sintered structure with a large amount of foreign material (probably oxide) at the grain boundaries (Figure 7). The welded overlay microstructures, too, are not all the same. The material from the bands of the M549 projectile shows the columnar grains expected in a welded structure (Figure 8) and the materials from the bands of the M483 and the M650 projectiles have been recrystallized by heat treatment to small equiaxed grains (Figures 9 and 10 respectively).

X-ray diffraction studies were made on the band materials from the M483,

M549, and M650 projectiles. As expected from its microstructure, the band material from the M549 projectile showed large grains and preferred crystalline orientation. However, both the other band materials showed only little crystalline orientation. Therefore, the welded overlay band materials did not all possess crystalline orientation; so this is not an explanation for their different sliding behaviors.

Excluding the data on aluminum bronze and the welded overlay band materials, there was a correlation of wear with hardness. The effect of hardness, however, was different for the different mating surfaces. Chromium electroplate, 4340 steel, and tantalum form a series of materials with very different hardnesses and their effects on the wear of the mating materials are also very different. (Of course, since their chemical properties, etc. are also very different, hardness could well not be the important property.) The data is plotted in Figure 11. There was always wear for all alloys sliding on tantalum with less wear for the harder alloys. The wears of copper alloys sliding on steel and on chromium were similar. No wear was measured if the alloys were harder than about 86 KHN. If the copper alloys were softer than this, their wear sliding on steel was about double that obtained sliding on chromium. The wear data for aluminum bronze and the welded overlay band materials, all of which had hardnesses of about 140 KHN, did not fit this correlation. With the exception of hardness, no other property of the copper alloys could be correlated with wear.

If wear is examined from a theoretical basis, it can be seen that this correlation of wear with hardness would be expected only for very similar materials. No wear should occur if rupture on sliding is along the original

interface; wear should only occur if rupture occurs within the body of the metal. Therefore, wear should be expressed by the following equation:

$$W = kA^*f(H) - B \qquad (1)$$

where:

W = wear

k, B = constants

A^* = area of metal ruptured

$f(H)$ = function of hardness

Wear would actually be a function of cohesive strength but this is usually a function of the hardness of the metal.[13] The constant, B, was added to the expression because there is a threshold effect, i.e., if the cohesive strength of the metal is high enough, it will not rupture. This expression does relate wear to hardness as is frequently observed, but it also points out the fact that if the constants and the function of hardness vary from metal to metal, wear would not be a simple function of hardness regardless of the metal pair. Hardness is important but if the materials are sufficiently different, harder materials may well wear more than softer as in this study.

Friction

The adhesion explanation of friction for smooth surfaces has a great deal of evidence to support it. While modifications can be argued in some cases, it is doubtlessly correct in the main. In this picture the tips of the asperities adhere or "cold weld" during sliding, and the force of friction is the force necessary to break these bonds or to rupture the bulk metal below the interface. This can be formulated as:

$$F = k_1(\delta_1 A_{dis} + \delta_2 A_{undis}) + k_2 A^* e_c \qquad (2)$$

where:

F = friction force

k_1, k_2 = constants

δ_1 = metal-to-metal adhesion

δ_2 = metal-to-surface film adhesion

A_{dis} = contact area with disrupted surface film

A_{undis} = contact area of undisrupted surface film

A^* = area of metal ruptured

e_c = cohesive strength of weaker metal

The value of the metal-to-surface film adhesion is almost always very much less than the value of the metal-to-metal adhesion so the term involving this quantity can probably be eliminated in the cases of interest.[4-6,26] Furthermore, the real area of contact will be proportional to the hardness of the softer metal[22,24] and the proportion of surface film which is disrupted will also be a function of hardness.[6,23,27] In addition, cohesive strength is also usually a function of hardness.[23]

Therefore:

$$F = k_1\delta_1 f_1(H) + k_2 A^* f(H) \qquad (3)$$

Friction thus would not often be a simple function of either adhesive strength or hardness. Usually, the ratio of k_1 to k_2, A^*, and δ_1, as well as the relationship between hardness and cohesive strength all differ from metal to metal and often from one set of conditions to another.

As expected, the coefficients of friction measured in these experiments could not be correlated with any bulk property including modell. However,

since the hardness of the slider was always considerably less than that of the plate (except in the cases of some of the alloys sliding on tantalum), a correlation with modell (or hardness with similar values of elasticity) would not be expected on the basis of the work of Moore and Tegart[13] or Montgomery.[12]

The correlation of friction with adhesion between the surfaces could not be tested because adhesion was not measured. However, such a correlation seems unlikely because of the large difference in friction of copper containing 0.31 and 1.20 percent Fe sliding on steel and OFHC and sintered copper sliding on both steel and chromium. The adhesions of these alloys would be expected to be quite similar.

Although the effect of load on the coefficients of friction was not investigated in more than a few cases, some examples are plotted in Figure 12. The coefficients of friction were high at low loads and decreased asymptotically as the load increased. At loads greater than about 890 N (200 lbf) there was usually little further change with load. This was the general behavior found by McFarlane and Tabor.[17] The exact friction-load curve was different for all metal pairs investigated.

CONCLUSIONS

1. It was not possible to correlate metal transfer, scuffing (rough deposits), wear, or friction with the properties of the metal pair except for the one exception discussed below. It must be admitted, however, that the sliding behaviors of the copper alloys were expected to be irregular perhaps because of their propensity to work harden.

2. Excluding the data on aluminum bronze and the welded band materials, there was a correlation of wear with hardness with less wear with higher hardness. The effect of hardness was different for the different mating surfaces.

3. Mutual solubility with the disk metals and position in the periodic table did not control metal transfer and scuffing with the copper alloys investigated. While position in the periodic table is identical and mutual solubility is certainly very similar for most of the copper alloys, there were great differences in metal transfer and scuffing.

4. While there was a tendency for more transfer to occur at higher wear rates, heavy and very heavy transfer did occur even at very low rates. Heavy and very heavy transfer were not usually associated with high wear, and rough deposits were not usually associated with high wear or heavy transfer.

5. Metal transfer was not the first step in the production of loose wear particles with the copper alloys because there was wear sometimes without metal transfer. For most of the track there was only a single pass of the wearing pin.

6. Wear of aluminum bronze and the welded overlay band materials investigated was essentially different from the other copper alloys investigated. These alloys often scuffed and sometimes transferred to the mating surface more and showed unexpectedly high wear when sliding on steel and tantalum. The reason for this for the welded overlay band materials was not the result of a particular microstructure or crystalline orientation.

7. Small amounts of iron in the copper alloys did not result in scuffing and high metal transfer even when sliding on steel.

8. Generally, the wears of all the copper alloys were considerably less sliding on chromium electroplate than they were sliding on 4340 steel. This means that if greater wear on the rotating bands of the projectile is experienced by chromium plating the bore of a cannon as is frequently the case, the greater wear is doubtlessly caused by increased roughness of the bore.

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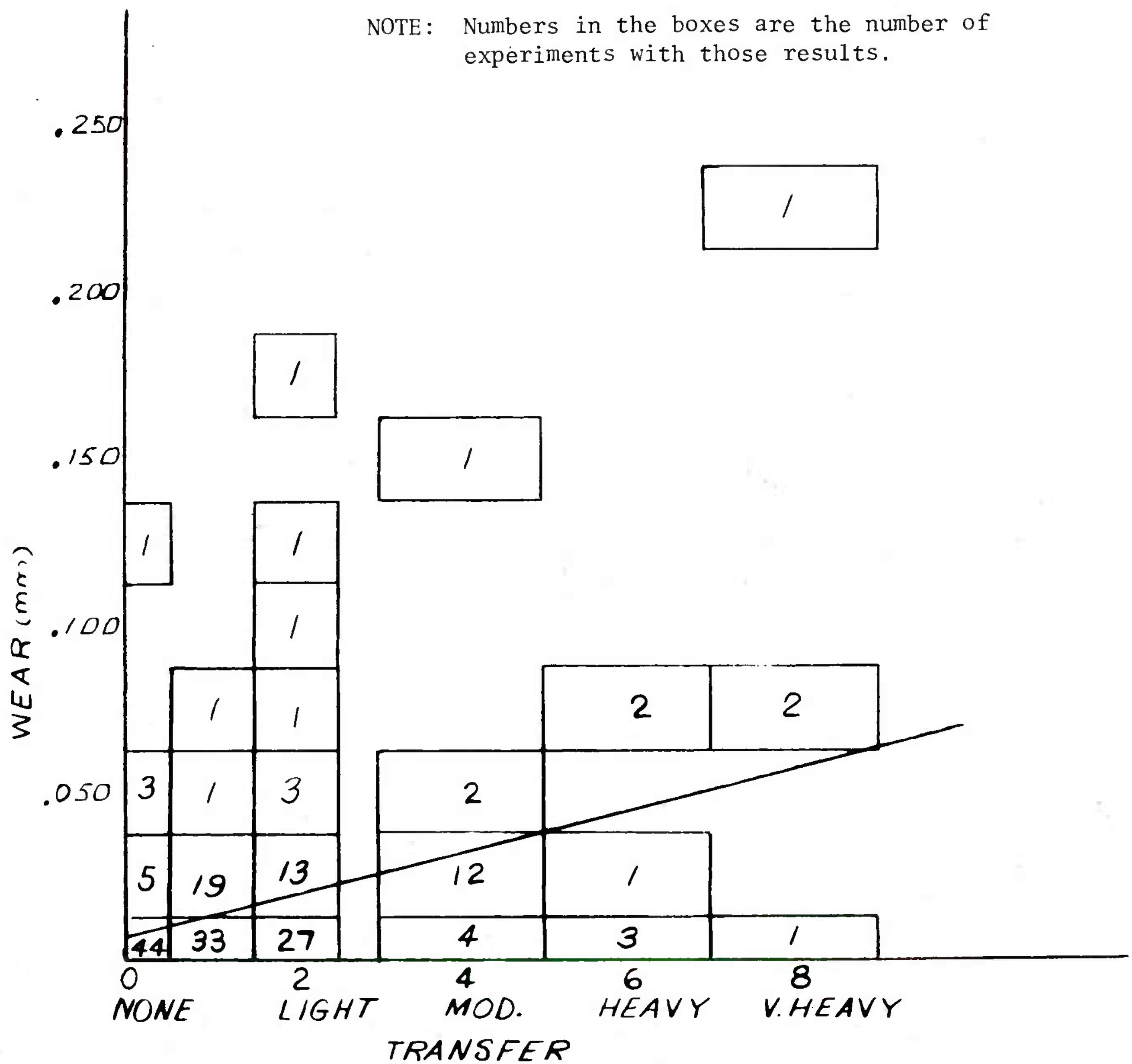

Figure 1. Wear as a Function of Metal Transfer.

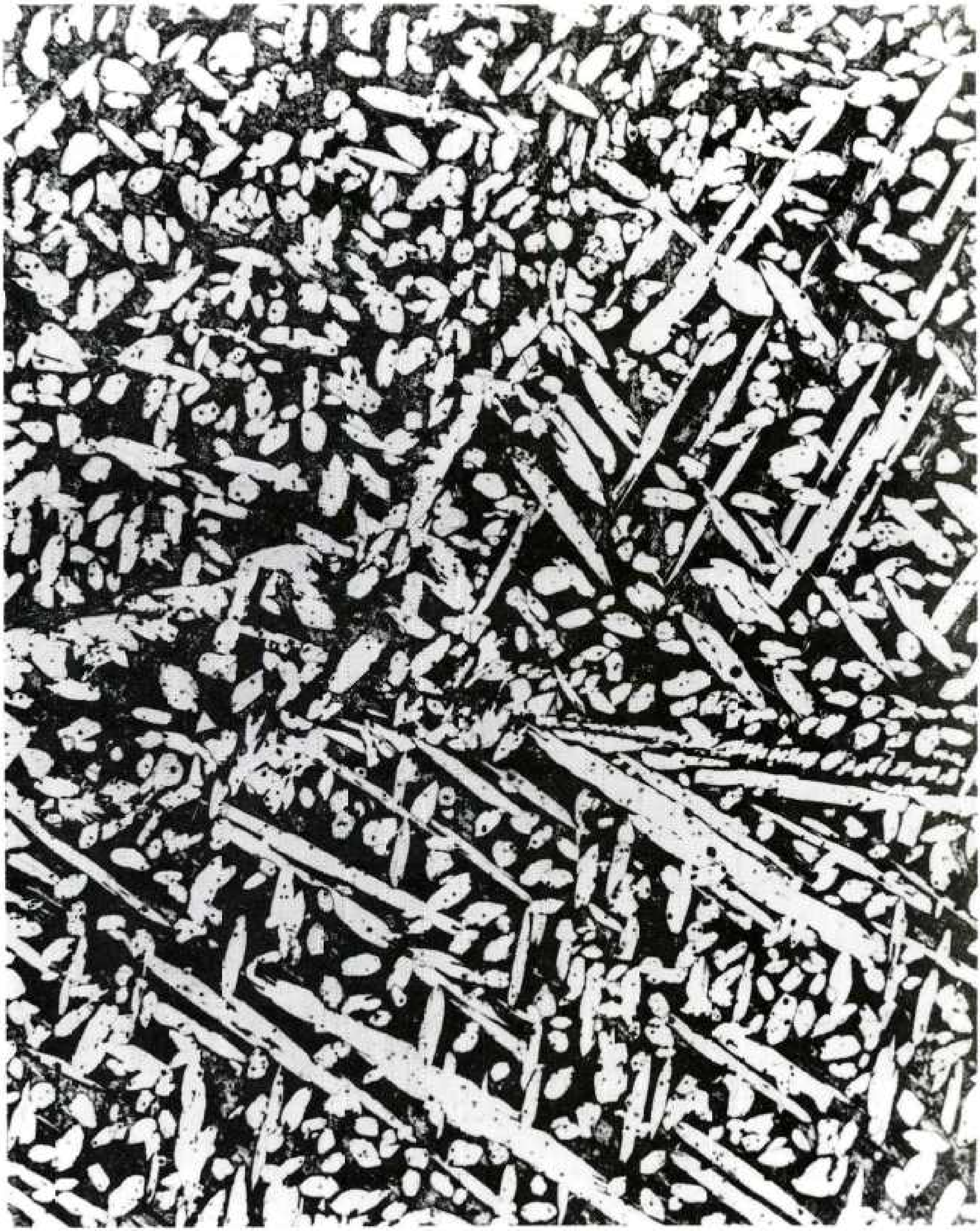

Figure 2. Microstructure of Aluminum Bronze (100X).

Figure 3. Microstructure of Gilding Metal (90% Cu/10% Zn) (100X).

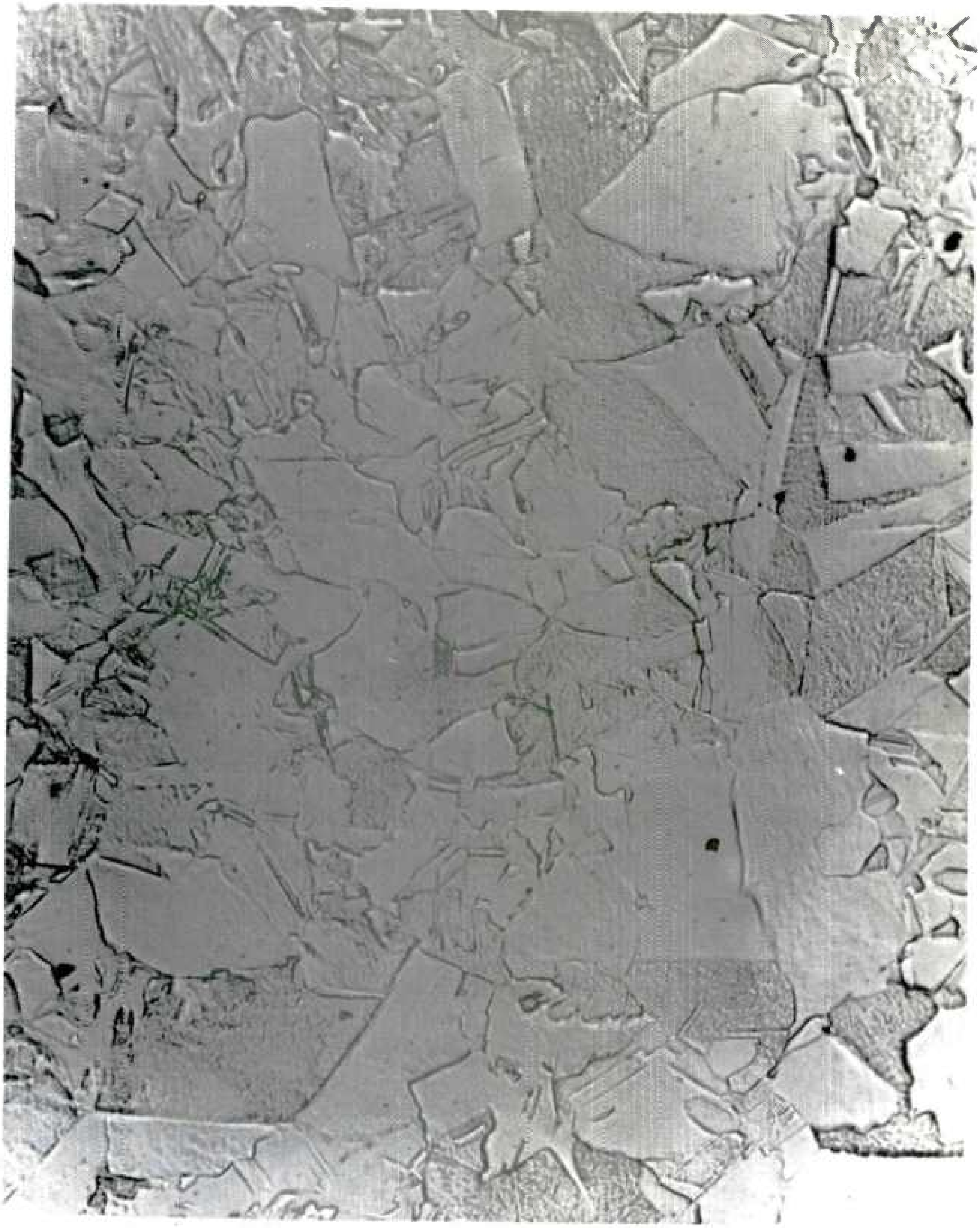

Figure 4. Microstructure of OFHC Copper (100X).

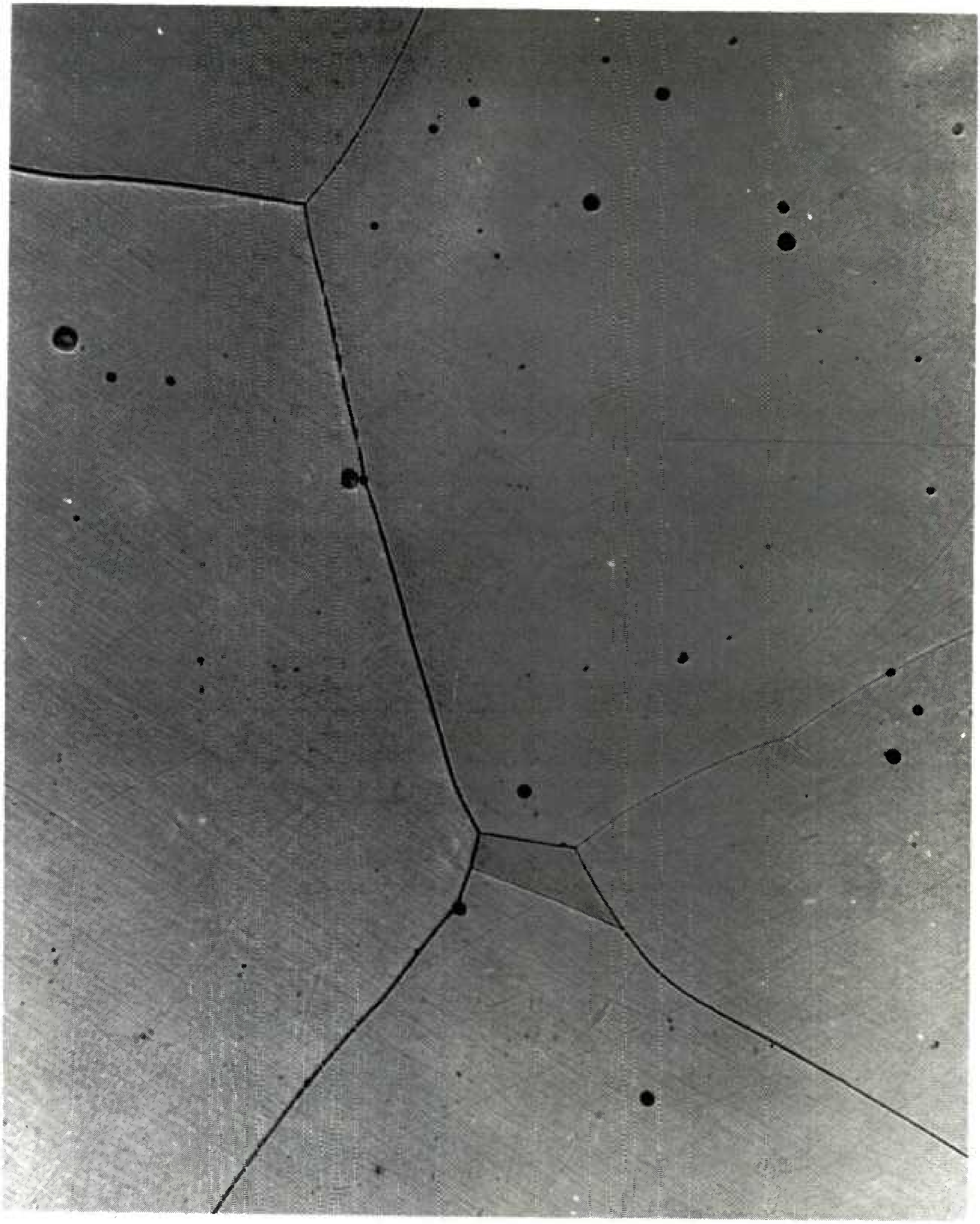

Figure 5. Microstructure of Copper Containing Either 0.31 or 1.20 wt. % Fe (200X).

Figure 6. Microstructure of Dispersion Hardened Coppers (1000X).

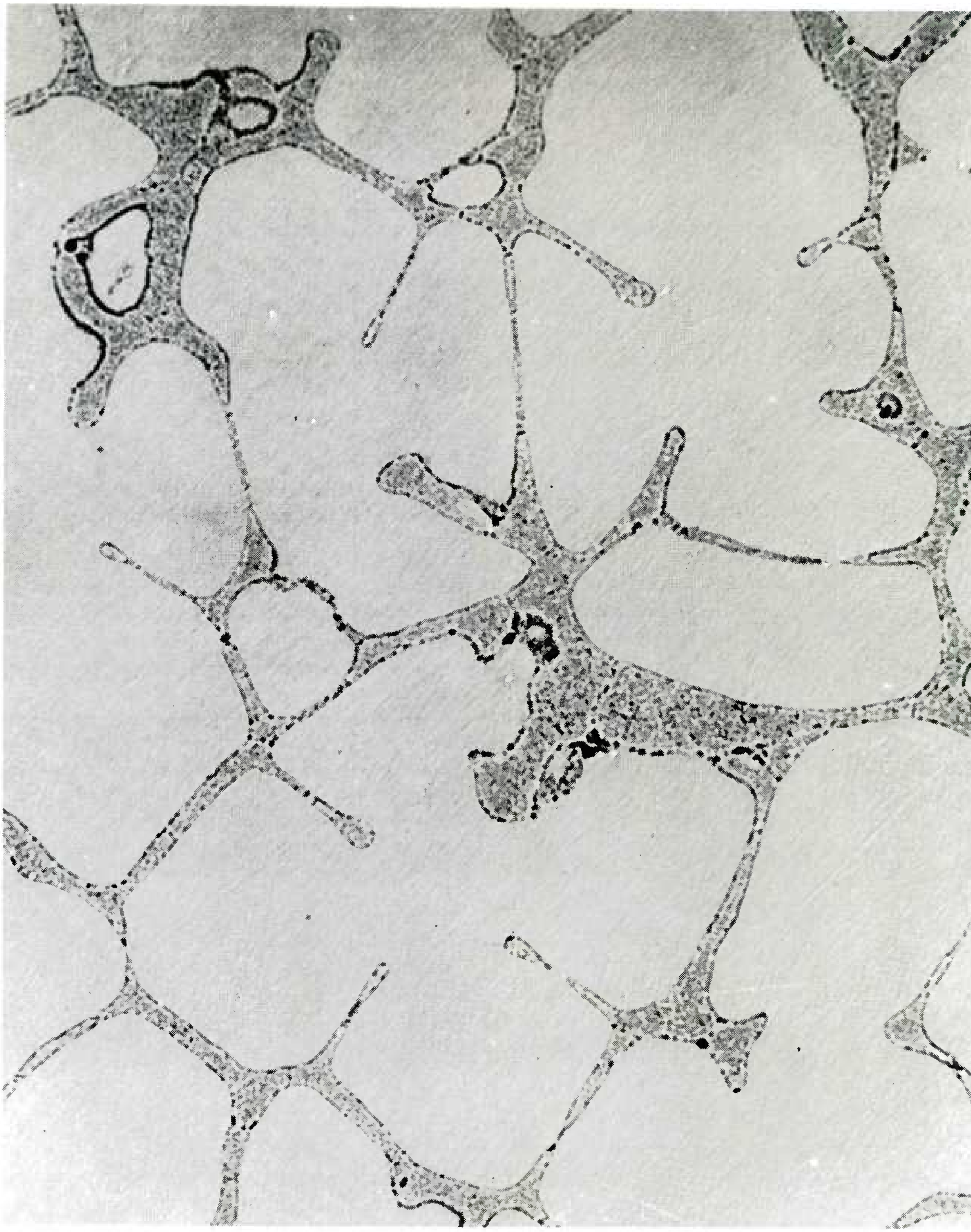

Figure 7. Microstructure of Sintered Copper (200X).

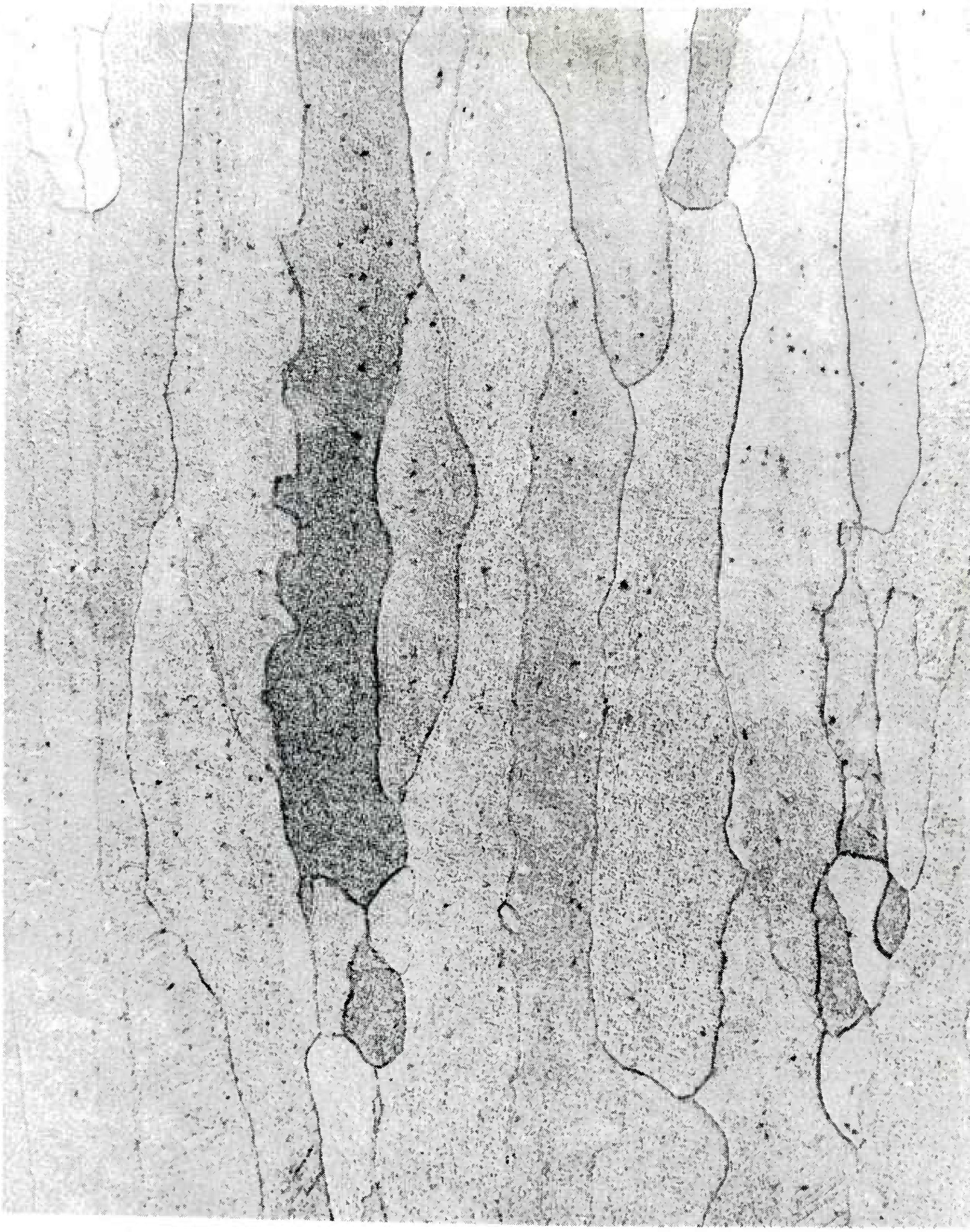

Figure 8. Microstructure of Band Material From M549 Projectile (100X).

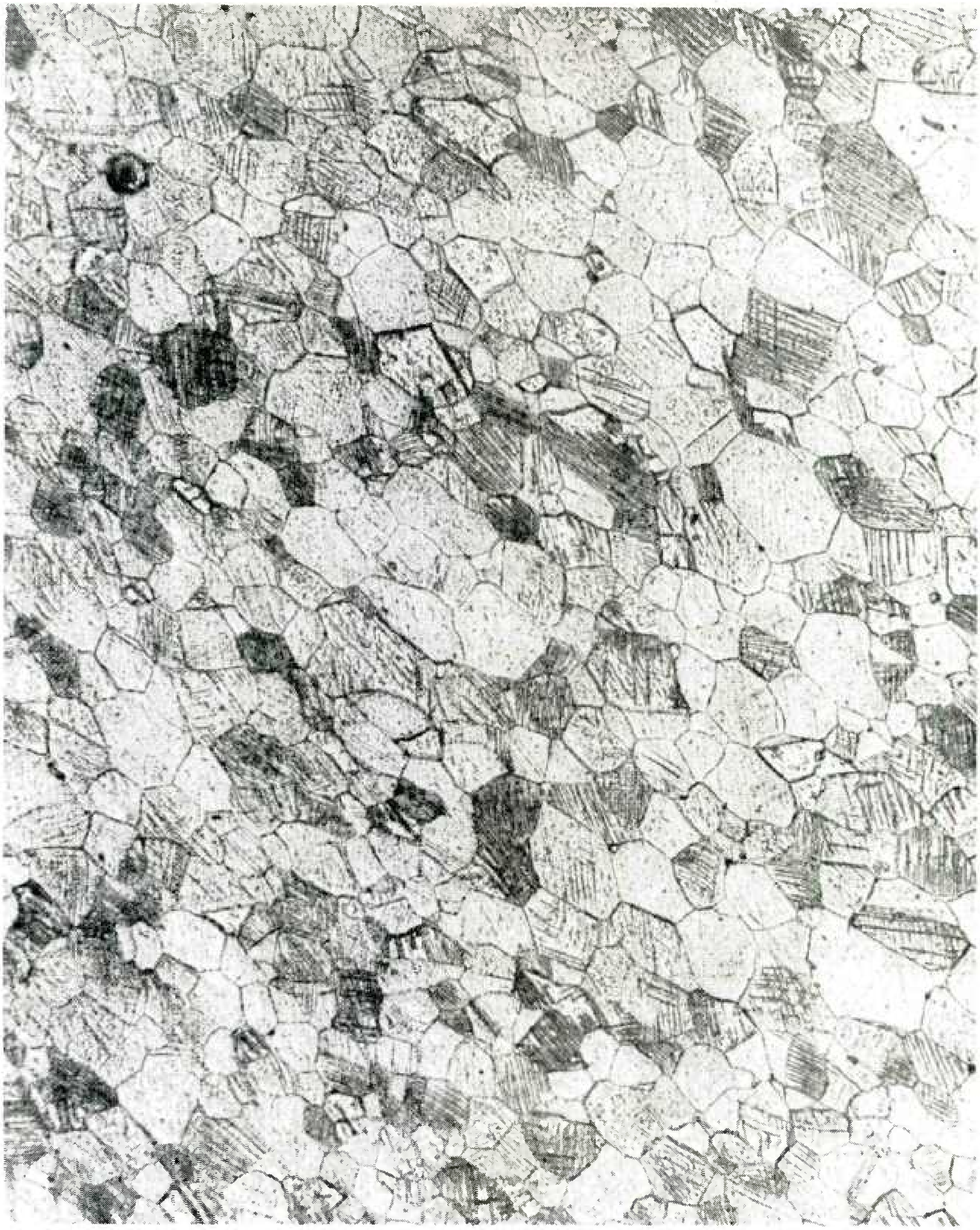

Figure 9. Microstructure of Band Material From M483 Projectile (200X).

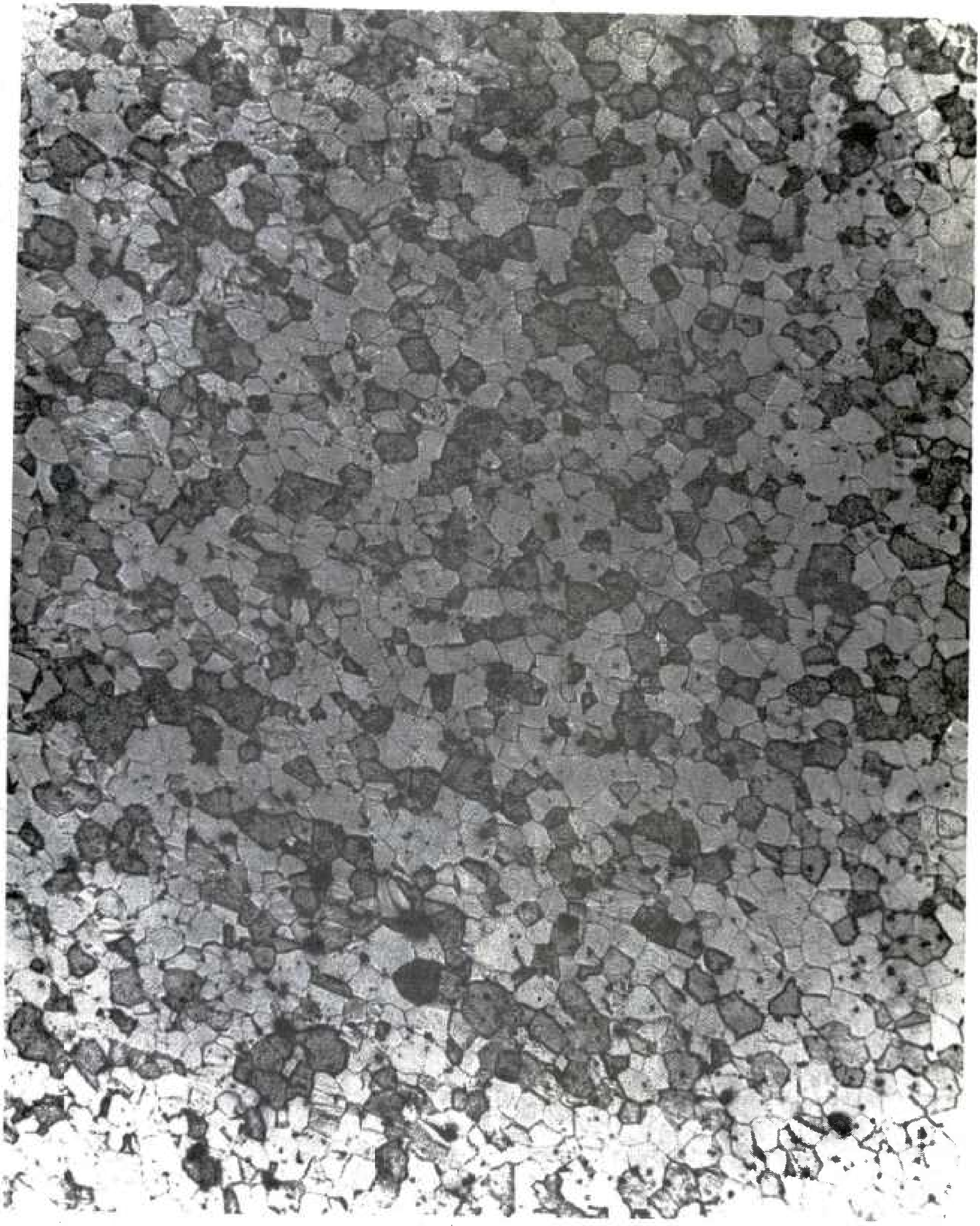

Figure 10. Microstructure of Band Material From M650 Projectile (100X)

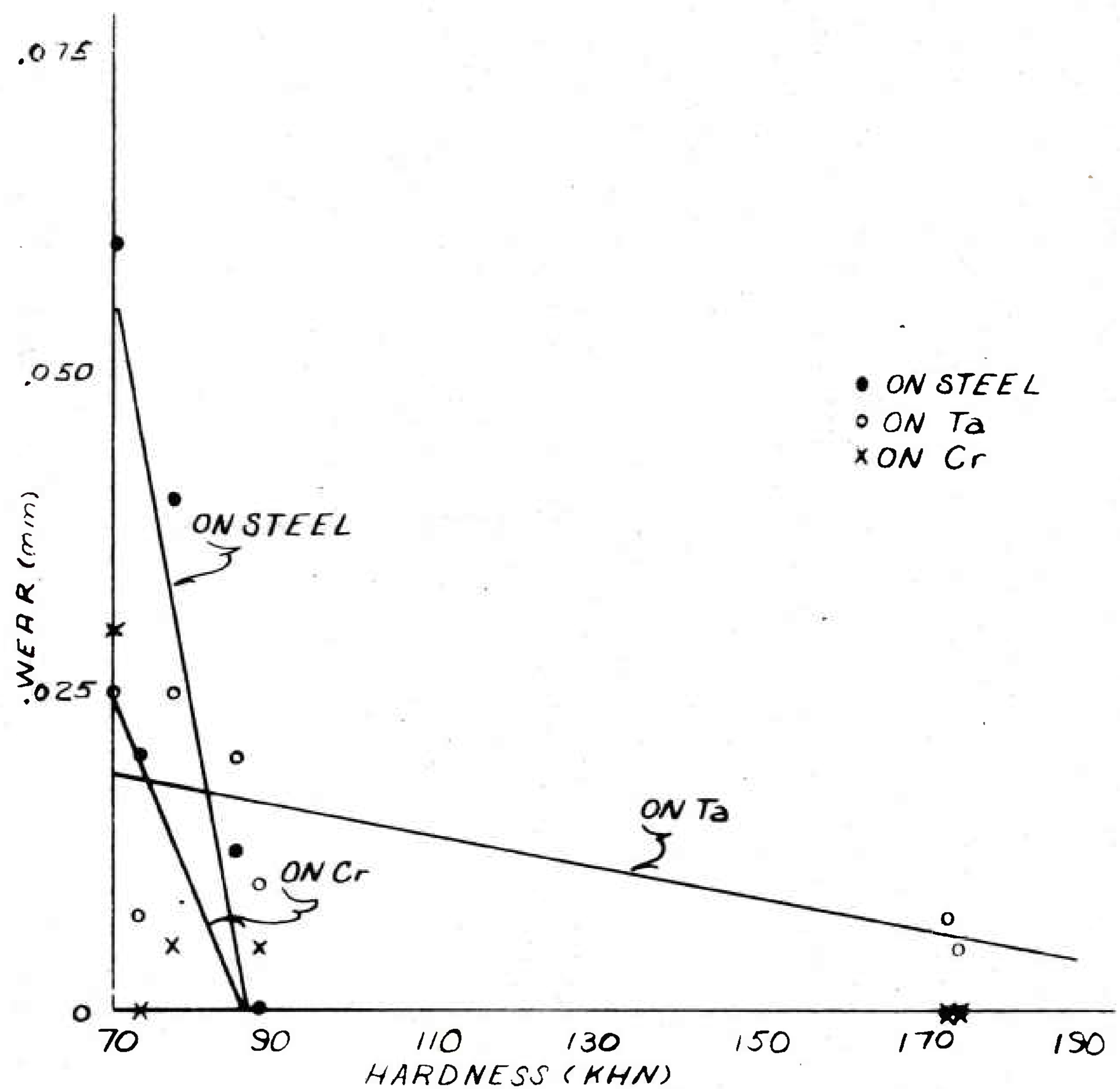

Figure 11. Effect of Hardness on Wear for Similar Copper Alloys.

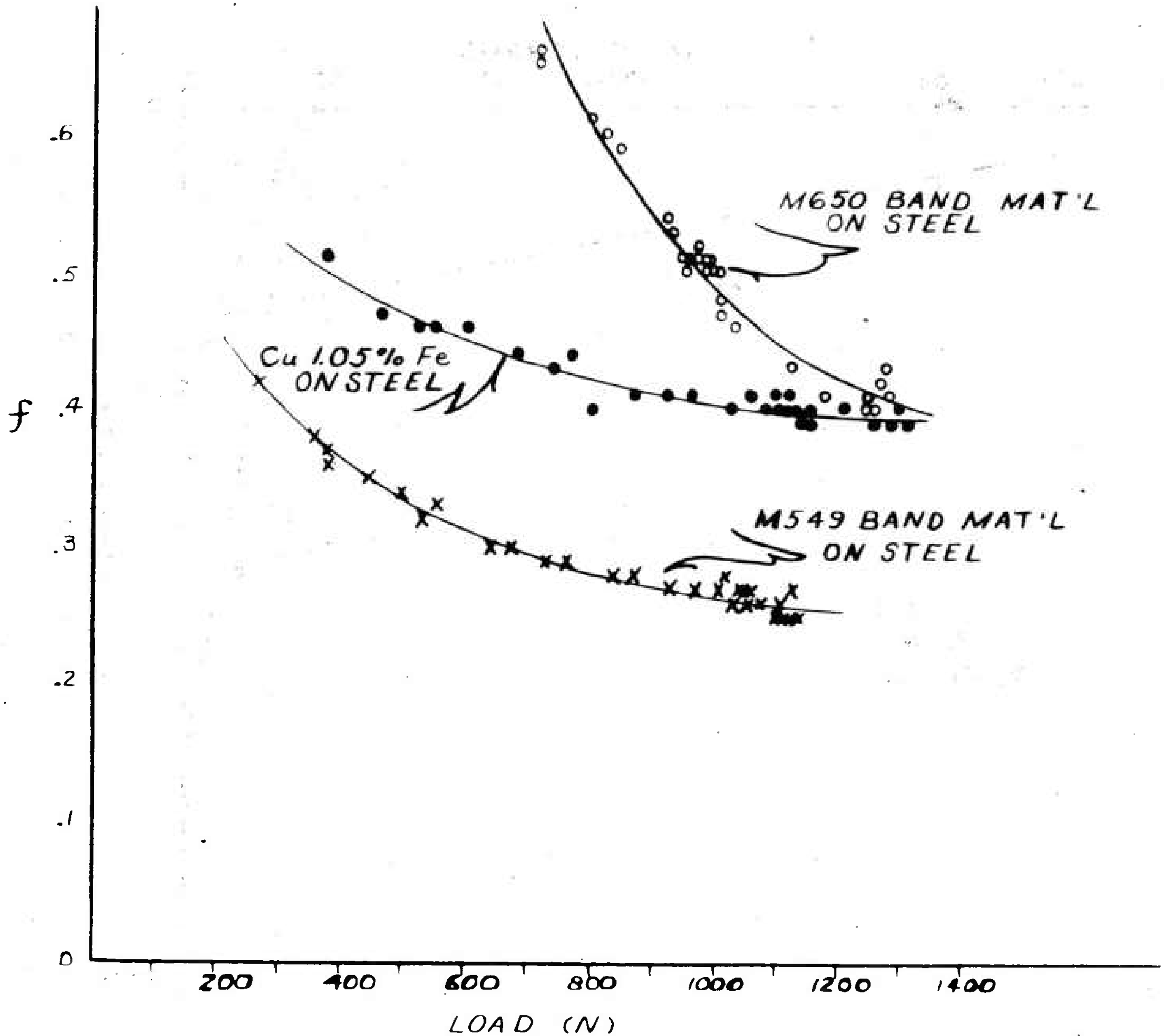

Figure 12. Effect of Load on Coefficients of Friction.

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